

Performance Analysis of Household Refrigerator with Alternate Refrigerants

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Abstract: This study presents a comparison of energy and exergy analysis for R134a, R152a, R290, R600 and R600a in refrigerator. The paper analyzes the domestic refrigerator with alternative refrigerants for computing coefficient of performance, exergy destruction ratio, exergy efficiency and efficiency defect. The method of exergy provides a measure to judge the magnitude of energy waste in relation to the energy supplied or transformed in the total plant and in the component being analyzed, a measure for the quality (or usefulness) of energy from the thermodynamic viewpoint and a variable to define rational efficiencies for energy systems. It is established that in the present work efficiency defect is maximum in condenser and lowest in evaporator. Comparison of various properties for alternative refrigerants has been done for a domestic refrigerator.

Keywords: Domestic refrigerator, Refrigerant, Exergy, Efficiency defect.

I. INTRODUCTION

In domestic refrigerator, a sealed unit consisting of (i) compressor and (ii) electric motor is used. The evaporator is the space inside the refrigerator cabinet (it is insulated to avoid any heat gained from the surrounding) in which evaporator coils on a box are provided. The box is called de-freeze. The heat is extracted by the evaporator from the food item kept inside the refrigerator. The refrigerant in the evaporator evaporates due to heat extracted. The vapours are sucked and compressed by the compressor in the sealed unit. The high pressure refrigerant vapours give away heat to the surrounding and get liquefied in the condenser generally mounted at rear of the refrigerator. Capillary is used to throttle high pressure liquefied refrigerant in to evaporator which has low pressure.

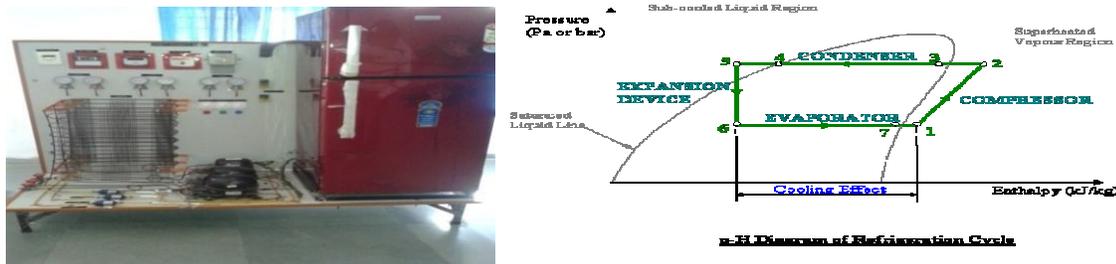


FIG. 1: DOMESTIC REFRIGERATOR

II. LITERATURE SURVEY

In recent past, R12 was used as working substance in domestic refrigerator. But use of R12 was abandoned because of ozone layer depletion (ODP) problem. Now a day, R134a is used as working substance in domestic refrigerator. R134a (hydrofluorocarbon refrigerant) is used in domestic refrigeration and other vapour compression system. R134a is having zero ozone depletion potential (ODP) and almost same thermodynamic properties as R12 (chlorofluorocarbon

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refrigerant), but it has 1300 global warming potential (GWP) per year which is very high as shown table 1. Although global warming is a good thing in itself and allows life to exist in all its variety but the concern is that man’s activities are increasing the concentration of carbon dioxide and other green gases in the atmosphere, causing the amount of absorbed infrared radiation to increase, and leading to atmospheric temperatures and consequent long term climate changes. The sale of R134a reported to AFEAS 1970-2003 [11] is significantly increasing during the past two decades. Hence, Kyoto protocol established the phased out of HFCs in the near future.

TABLE I: Properties of refrigerants

Refrigerant (Category)	Chemical Formula	Normal Boiling Point (°C)	Critical Temperature (°C)	ODP	GWP (per 100 Year)	Safety Group
R134a (HFC)	CF ₃ CH ₂ F	-26.07	101.06	0	1300	A1
R152a (HFC)	CH ₃ CHF ₂	-24.02	113.3	0	120	A2
R290 (HC)	C ₃ H ₈	-42.1	96.8	0	20	A3
R600	C ₄ H ₁₀	-0.56	153	0	20	A3
R600a	(CH ₃) ₃ CH	-11.67	135	0	20	A3

(Source:<http://www.ec.gc.ca/Air/default.asp?lang=En&n=4CA440F8-1>)

R. Cabello et al [1] studied the influence of the evaporating pressure, condensing pressure and superheating degree of the vapour on the exergetic performance of a refrigeration plant using three different working fluids R134a, R407c, R22. K. Senthil Kumar et al [2] studied the behavior of HCFC (Hydrochlorofluorocarbon) -123/ HC-290 refrigerant mixture computationally as well as experimentally and found that refrigerant mixture 7/3 as a promising alternative to R12 system. B.O. Bolaji et al [3] investigated experimentally the performances of three ozone friendly Hydrofluorocarbon (HFC) refrigerants R12, R152a and R134a. R152a refrigerant found as a drop in replacement for R134a in vapour compression system. B.O. Bolaji [4] discussed the process of selecting environmental-friendly refrigerants that have zero ozone depletion potential and low global warming potential. R23 and R32 from methane derivatives and R152a, R143a, R134a and R125 from ethane derivatives are the emerging refrigerants that are non toxic, have low flammability and environmental-friendly. These refrigerants need theoretical and experimental analysis to investigate their performance in the system. A.S. Dalkilic et al [5] studied the performance analysis of alternative new refrigerant mixtures as substitute for R12, R134a and R 22. Refrigerant blend of R290/R 600a (40/60 by wt. %) and R 290/R1270 (20/80 by wt. %) are found to be the most suitable alternative among refrigerants tested for R12 and R22. S. Wongwises et al [6] found that 6/4 mixture of R290 and R600 is the most appropriate refrigerant to replace HFC134a in a domestic refrigerator. K Mani et al [7] found that R290/R600a (68/32 by wt. %) can be considered as a drop in replacement for R12 and R134a. Bukola O. Balaji et al [8] investigated the exergetic performance of R12 and its substitute (R134a and R 152a) in the domestic refrigerator. R152a performed better than R134a in terms of COP, exergetic efficiency and efficiency defect as R12 substitute in domestic refrigeration system. Alka Bani Agrawal et al [9] worked on eco-friendly refrigerant as a substitute for CFC (Chlorofluorocarbon). The binary mixture in the ration of 64% and 36% of R290 and R600a found to be a retrofit or drop in substitute of R12 for use in the vapour compression refrigeration trainer. Akhilesh Arora et al [10] had worked on a detailed analysis of an actual vapour compression refrigeration cycle. A computational model had been developed for computing coefficient of performance, exergy destruction, exergetic efficiency and efficiency defects for R502, R404A and R507A. The investigation had been done for evaporator and condenser temperatures in the range of -50°C to 0°C and 40°C to 55°C respectively. The results indicate that R507A was a better substitute to R502 than R404A. Miguel Padilla et al [11] found that R413A (mixture of 88% R134a, 9%R218, 3%R600a) can replace R12 and R134a in domestic refrigerator. M.M. El-Awad [12]

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performed the validation of model against experimental data that compared the performance of liquefied petroleum gas (LPG) to that of refrigerant R12 for domestic refrigeration.

Though a lot of work has already for comparison of properties of refrigerants but limited work is available in the literature regarding exergy analysis of various refrigerants for a domestic refrigerator.

III. MATHEMATICAL FORMULATION FOR EXERGY AND ENERGY ANALYSIS

A. Exergy Analysis

A detailed exergy analysis includes calculating exergy destruction, exergy loss, exergetic efficiency, and exergy destruction ratio in each component of the system along with the overall system. The exergy destruction is the amount of exergy that is lost to the environment and cannot be used anywhere, e.g. due to system irreversibilities. The exergy loss represents the amount of exergy that is transferred from the analyzed system to some other system. Overall, in a control volume the steady-state exergy balance can be expressed as:

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} - \left[\sum \left(\dot{Q} \left(1 - \frac{T_o}{T} \right) \right)_{in} + \sum \left(\dot{Q} \left(1 - \frac{T_o}{T} \right) \right)_{out} \right] \pm \dot{W} - \dot{E}_D = 0 \quad (2.1)$$

where \dot{E}_{in} , \dot{E}_{out} , \dot{Q} , \dot{W} and \dot{E}_D denote, respectively the exergy flow rate of stream entering a component or system, exergy flow rate of stream leaving a component or system, heat flow rate, mechanical work transfer to or from the control volume and rate of exergy destruction, subscript "0" denotes the extensive property of the system brought in the restrictive dead state.

1) Exergy Destruction of Evaporator:

$$\sum \dot{E}_6 - \sum \dot{E}_1 + \dot{Q}_{Evap} \left(1 - \frac{T_o}{T_r} \right) - \dot{E}_{D,Evap} = 0$$

$$\dot{E}_{D,Evap} = \dot{m}_r (h_6 - T_o s_6) - \dot{m}_r (h_1 - T_o s_1) + \dot{Q}_{Evap} \left(1 - \frac{T_o}{T_r} \right) \quad (2.2)$$

2) Exergy Destruction of Compressor:

$$\sum \dot{E}_1 - \sum \dot{E}_2 + \dot{W}_{Comp} - \dot{E}_{D,Comp} = 0$$

$$\dot{E}_{D,Comp} = \dot{m}_r (h_1 - T_o s_1) - \dot{m}_r (h_2 - T_o s_2) + \dot{W}_{Comp}$$

$$\dot{E}_{D,Comp} = \dot{m}_r (h_1 - T_o s_1) - \dot{m}_r (h_2 - T_o s_2) + \dot{m}_r (h_2 - h_1)$$

$$\dot{E}_{D,Comp} = \dot{m}_r (T_o (s_2 - s_1)) \quad (2.3)$$

3) Exergy Destruction of Condenser:

$$\sum \dot{E}_2 - \sum \dot{E}_5 - \dot{E}_{D,Cond} = 0$$

$$\dot{E}_{D,Cond} = \dot{m}_r (h_2 - T_o s_2) - \dot{m}_r (h_5 - T_o s_5) \quad (2.4)$$

4) Exergy Destruction of Expansion Device (Capillary Tube):

$$\sum \dot{E}_5 - \sum \dot{E}_6 - \dot{E}_{D,Exp} = 0$$

$$\dot{E}_{D,Exp} = \dot{m}_r (h_5 - T_o s_5) - \dot{m}_r (h_6 - T_o s_6)$$

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$$\dot{E}_{D,Exp} = \dot{m}_r (T_o (s_6 - s_5)) \quad (2.5)$$

5) Total Exergy Destruction:

$$\dot{E}_{D,Tot} = \dot{E}_{D,Evap} + \dot{E}_{D,Comp} + \dot{E}_{D,Cond} + \dot{E}_{D,Exp} \quad (2.6)$$

6) Product Exergy Rate:

$$\dot{E}_p = \dot{Q}_{Evap} \left[\left(1 - \frac{T_o}{T_r} \right) \right] \quad (2.7)$$

7) Fuel Exergy Rate:

$$\dot{E}_F = \dot{W}_{Comp} \quad (2.8)$$

8) Exergy Balance Equation Applied to the Whole System:

$$\dot{E}_F = \dot{E}_p + \dot{E}_{D,Tot} \quad (2.9)$$

9) Exergy Efficiency:

$$Ex_{eff} = \frac{\dot{E}_p}{\dot{E}_F} = \frac{\dot{Q}_{Evap} \left[\left(1 - \frac{T_o}{T_r} \right) \right]}{\dot{W}_{Comp}} = \frac{COP_{vcr}}{COP_{rr}} \quad (2.10)$$

Where COP_{vcr} is coefficient of performance of vapour compression cycle and COP_{rr} is the coefficient of performance of reversible refrigerator operating between T_o and T_r .

Exergetic efficiency measures the irreversibilities of real operation with respect to theoretical possible operation.

10) Efficiency Defect:

$$EffiDefect_k = \frac{\dot{E}_{D,k}}{\dot{W}_{Comp}} \quad (2.11)$$

Where k stands for particular component.

11) Exergy Destruction Ratio(EDR):

$$EDR = \frac{\dot{E}_{D,Tot}}{\dot{E}_p} = \frac{COP_{rr}}{COP_{vcr}} - 1 = \frac{1}{\eta_{ex}} - 1 \quad (2.12)$$

B. Energetic Performance

The overall energetic performance of refrigeration is determined by evaluating its coefficient of performance (COP)

$$COP = \frac{\dot{Q}_{Evap}}{\dot{W}_{Comp}} \quad (2.13)$$

IV. RESULT AND DISCUSSTION

Data assumed for the analysis are given below:

- a) Mass flow rate of refrigerant (\dot{m}_r) is one kg/s.
- b) Degree of subcooling of liquid refrigerant is 4°C and degree of super heating of vapour refrigerant is 4°C.
- c) Isentropic efficiency of compressor is 75%.
- d) Range of evaporator temperature is -40°C to 0°C in a step of 4°C.
- e) Present analysis is carried out at condenser temperature of 40°C and 55°C.
- f) Pressure drop in evaporator is 0.1bar and condenser is 0.25bar.
- g) Dead state temperature is 25°C.

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- h) Difference between evaporator and space temperature ($T_r - T_e$) is 12°C.
- i) Thermal exergy loss in condenser is neglected as the boundary of the condenser is assumed to be at the environment temperature.

A program is made for energy and exergy analysis of system in Engineering Equation solver software.

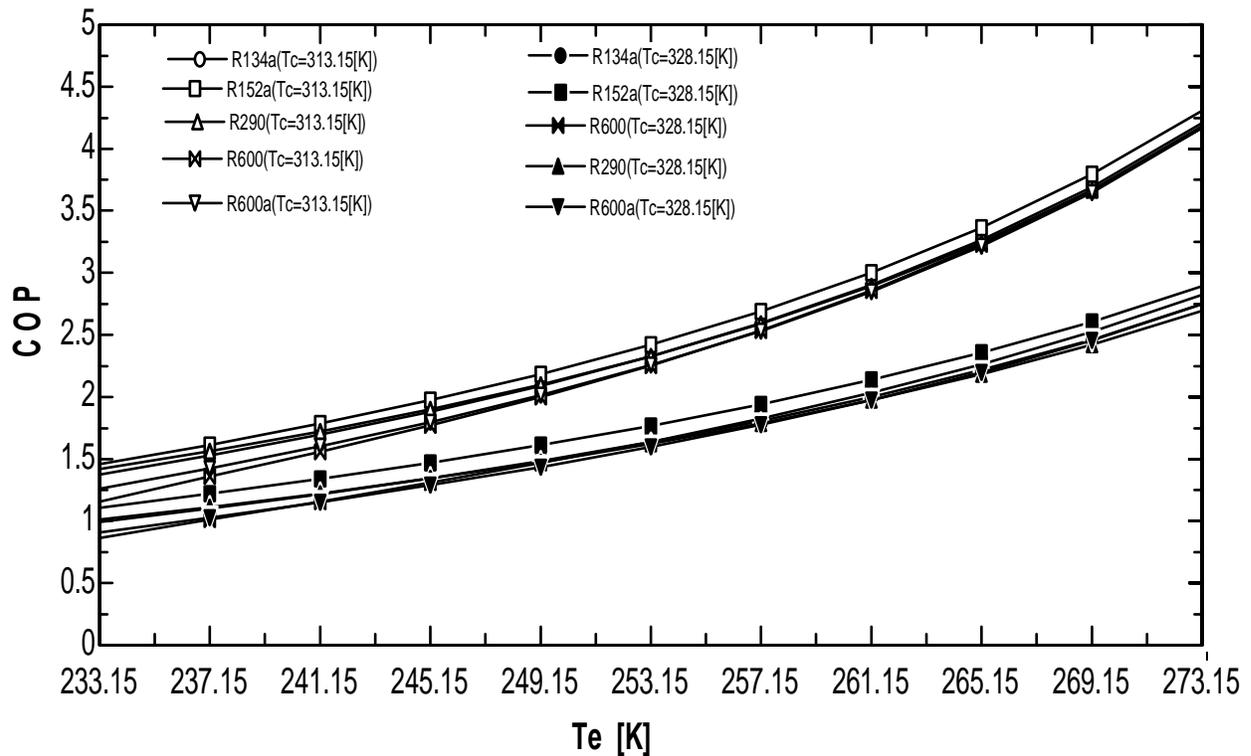


Fig. 2: Variation of coefficient of performance with evaporator temperature for different refrigerants

Fig. 2 shows the variation of coefficient of performance with evaporator temperature. Figure represents a progressive increase in coefficient of performance with increase in evaporator temperature because refrigerating effect increase and work of compression decrease with increase in evaporator temperature. R152a has highest value of coefficient of performance followed by R290, R134a, R600a and R600 at 40°C but at 55°C R152a has highest value of coefficient of performance followed by R134a, R600, R290 and R600a.

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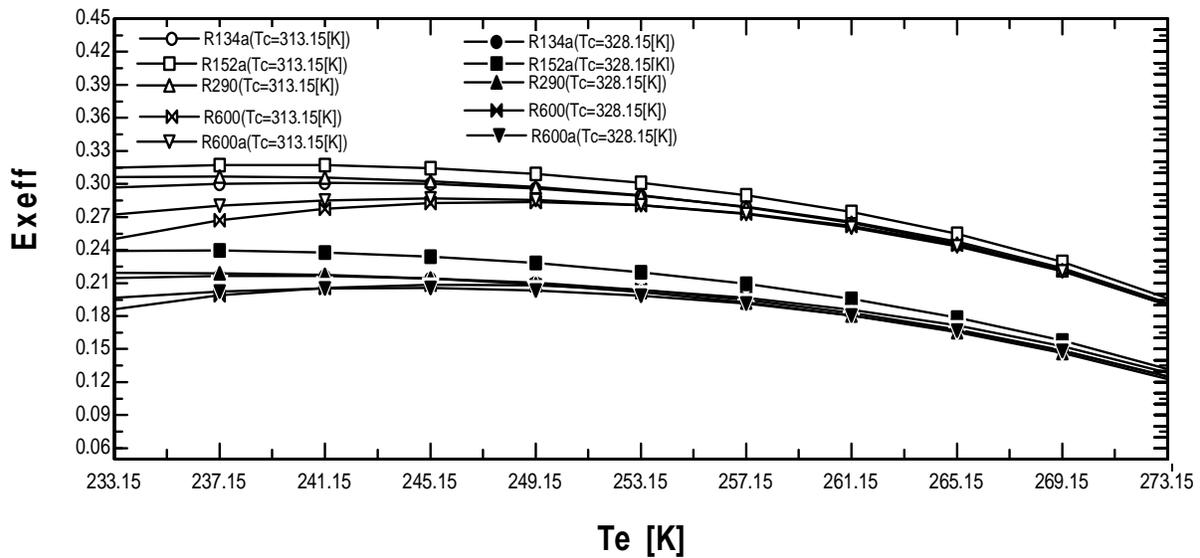


Fig. 3: Variation of exergetic efficiency with evaporator temperature for different refrigerants

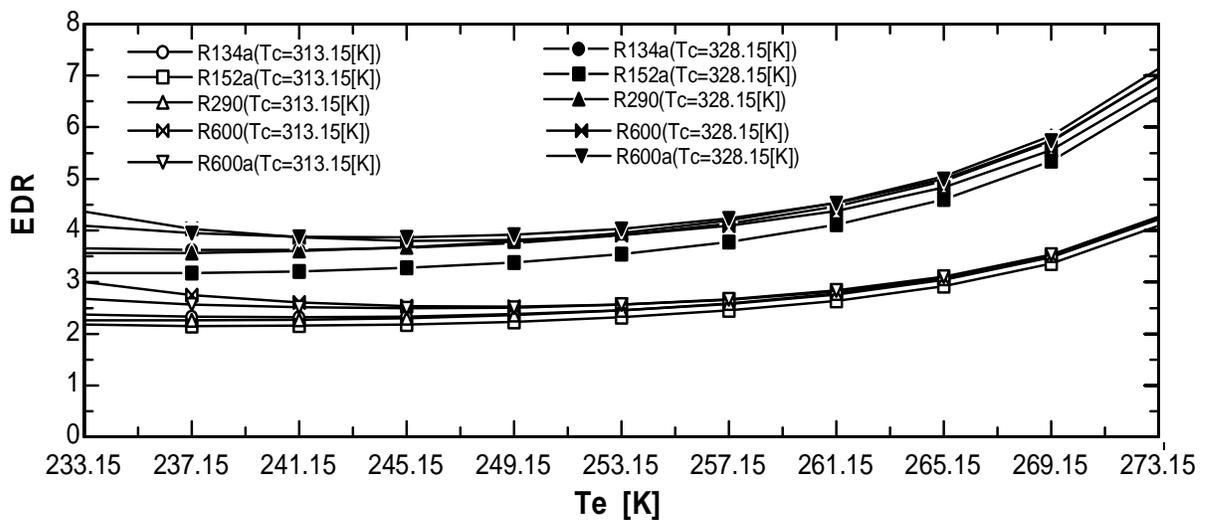


Fig. 4: Variation of EDR with evaporator temperature for different refrigerants

Fig. 3 and 4 shows the variation of EDR and exergetic efficiency with evaporator temperature. Rise and fall of exergetic efficiency curve is because of the fact that with increase in evaporator temperature, value of \dot{Q}_{Evap} and \dot{W}_{Comp} increases whereas value of $\left(1 - \frac{T_o}{T_r}\right)$ decreases. R152a has the highest value of exergetic efficiency followed by R290, R134a, R600a and R600 at 40°C but at 55°C R152a has highest value of exergetic efficiency followed by R134a, R290, R600 and R600a. The order is opposite in case of EDR.

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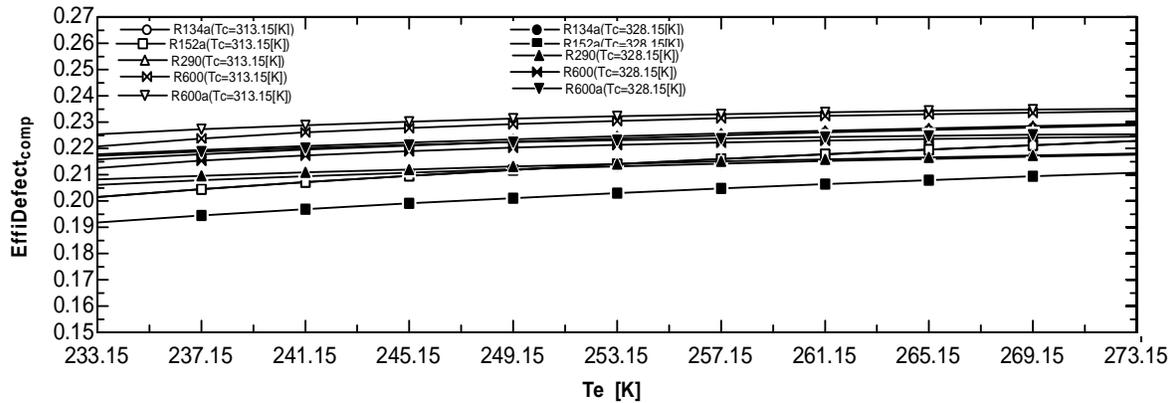


Fig. 5: Variation of efficiency defect in compressor with evaporator temperature for different refrigerants

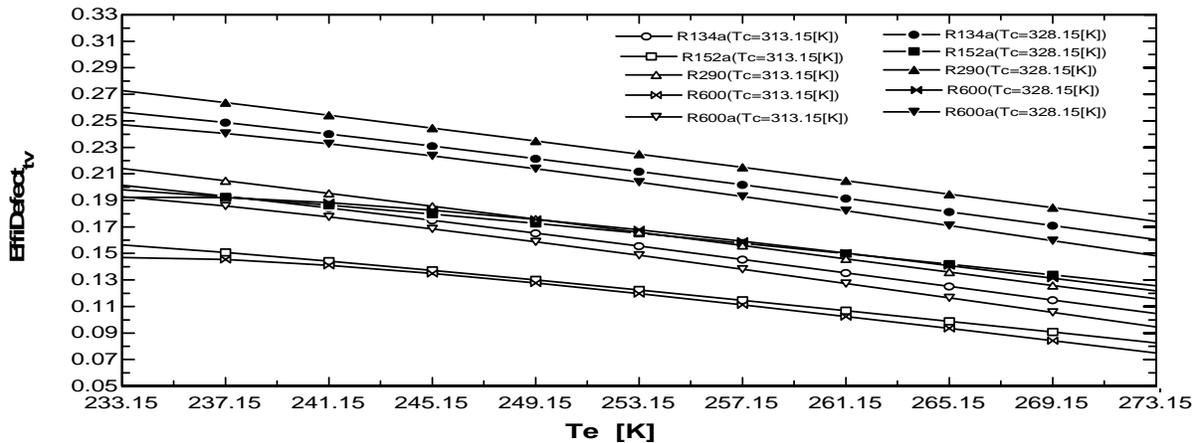


Fig. 6: Variation of efficiency defect in throttle valve with evaporator temperature for different refrigerants

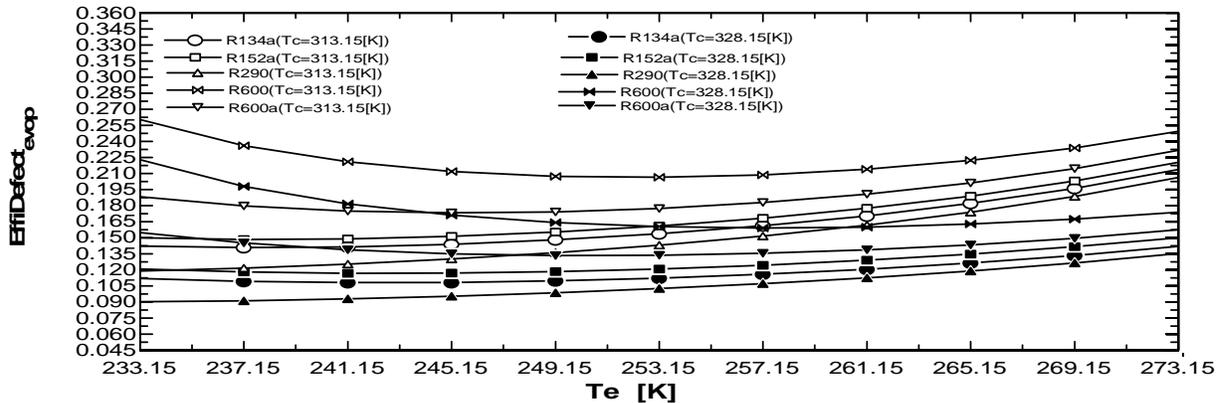


Fig. 7: Variation of efficiency defect in evaporator with evaporator temperature for different refrigerants

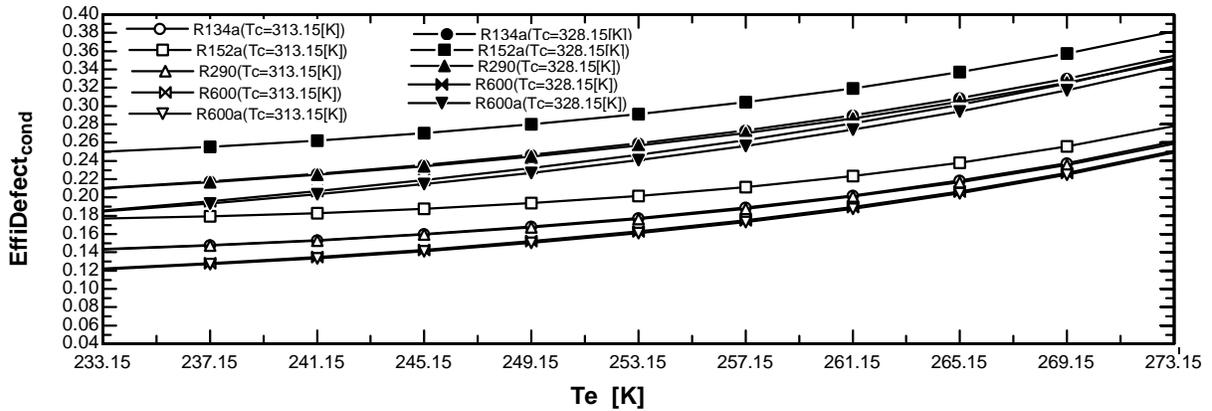


Fig. 8: Variation of efficiency defect in condenser with evaporator temperature for different refrigerants

Efficiency defect gives the idea of fraction of input energy destroyed in a particular component and helps in finding out worst component in a system. Fig. 5 points out that R600a have highest value of efficiency defect for compressor followed by R600, R290, R134a and R152a. Fig. 6 points out that R290 have highest value of efficiency defect for throttle valve followed by R134a, R600a, R152a and R600. Fig. 7 points out that R600 have highest value of efficiency defect for evaporator followed by R600a, R152a, R134a and R290. Fig. 8 points out that R152a have highest value of efficiency defect for compressor followed by R134a, R290, R600 and R600a. Efficiency defect is highest in compressor followed by condenser, evaporator and throttle valve at 40°C but at 55 °C efficiency defect is highest in condenser followed by compressor throttle valve and evaporator.

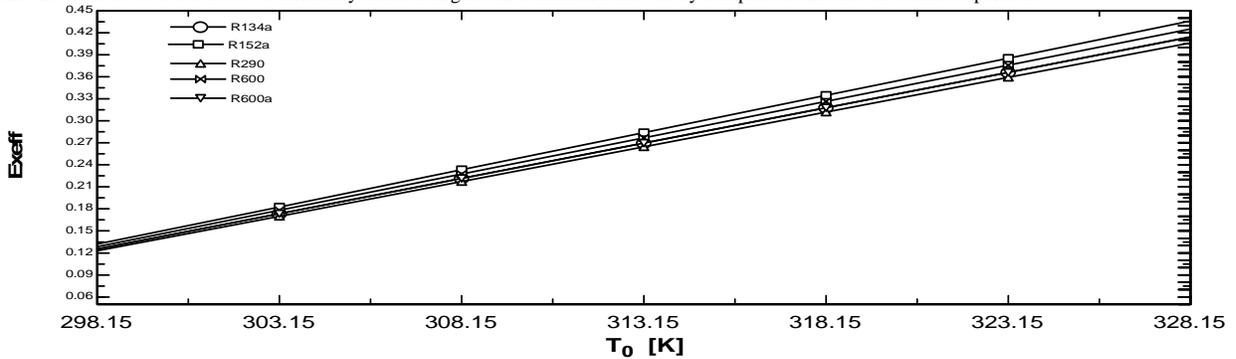


Fig. 9: Variation of exergetic efficiency with dead state temperature for different refrigerants ($T_e = 0^\circ\text{C}$, $T_c = 55^\circ\text{C}$)

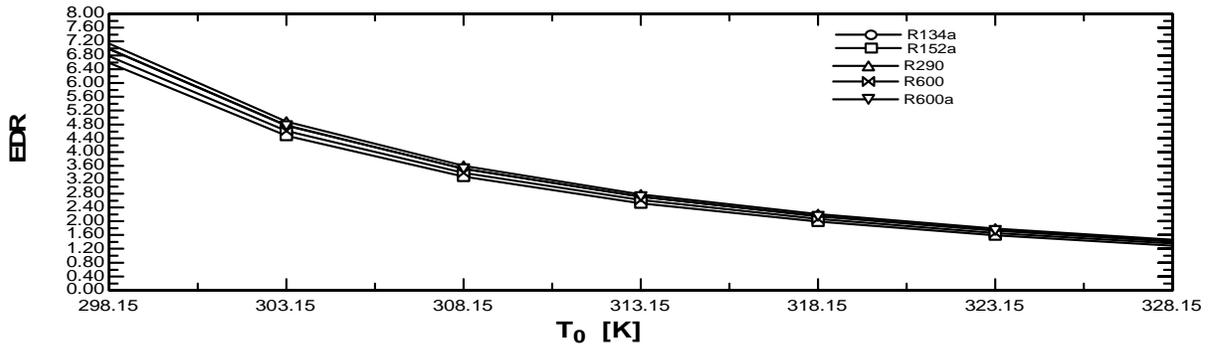


Fig. 10: Variation of EDR with dead state temperature for different refrigerants ($T_e = 0^\circ\text{C}$, $T_c = 55^\circ\text{C}$)

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Fig -9 and -10 shows the variation of exergetic efficiency and EDR with dead state temperature for different refrigerant. With increase in dead state temperature value of $\left(1 - \frac{T_o}{T_r}\right)$ decrease which result in increase in exergetic efficiency.

EDR value decreases because EDR is inversely proportional to exergetic efficiency. R152a has highest value of exergetic efficiency followed by R600, R600a, R134a and R290. The order is opposite in case of EDR.

V. CONCLUSION

Following conclusions are drawn from the present analysis:

- R152a has the highest value of coefficient of performance among R134a, R152a, R290, R600 and R600a.
- R152a has the highest value of exergetic efficiency among R134a, R152a, R290, R600 and R600a.
- R600 has the highest value of EDR among R134a, R152a, R290, R600 and R600a at 40°C but at 55°C R600a has the highest value of EDR among R134a, R152a, R290, R600 and R600a.
- R600a has the highest value of Efficiency defect in compressor among R134a, R152a, R290, R600 and R600a.
- R290 has the highest value of Efficiency defect in throttle valve among R134a, R152a, R290, R600 and R600a.
- R600 has the highest value of Efficiency defect in evaporator among R134a, R152a, R290, R600 and R600a.
- R152a has the highest value of Efficiency defect in condenser in evaporator among R134a, R152a, R290, R600 and R600a.
- Condenser has highest value of efficiency defect followed by compressor, throttle valve and evaporator.
- R152a has highest value of exergetic efficiency among R134a, R152a, R290, R600 and R600a when T_o varies between 25°C and 55°C, $T_e = 0^\circ\text{C}$, $T_c = 55^\circ\text{C}$ but R290 has highest value of EDR among R134a, R152a, R290, R600 and R600a for the same condition.

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